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Optimization Trilogy for Energy Management in Parallel Hybrid Electric Vehicles

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Abstract

This paper presents a model-based hybrid technique for energy management in parallel hybrid electric vehicles. The proposed hybrid algorithm uses combination of 3 different optimization techniques for energy management in parallel hybrid electric vehicles. The three different optimization techniques used are fuzzy logic, rule based and ECMS. The hybrid algorithm has 2 parts, in first part the mode of operations of parallel hybrid electric vehicles are done with the help of fuzzy logic and rule based. In second part the power request obtain in mode 3 (engine+ motor mode) is further optimized with help of ECMS. Japanese 15 mode driving cycle has been used for testing the hybrid algorithm. The result of hybrid algorithm is compared with ECMS only algorithm.

Keywords

Parallel electric hybrid vehicles, equivalent consumption minimization strategy, hybrid algorithm, fuel consumption, Rule based, Fuzzy logic.

Introduction

Numerous optimization techniques has been employed in previous years for energy management in parallel hybrid vehicles like dynamic programming, neural network, fuzzy logic, particle swarm optimization, rule based, genetic algorithm, equivalent consumption minimization strategy (ECMS) …etc but most of these methods used for energy management in parallel hybrid electric vehicles do not give optimal solution for fuel consumption. Dynamic programming although gives optimal result but the main disadvantage of dynamic programming is that it requires prior knowledge of driving cycle that is why dynamic programming can only be employed for offline scenario and cannot be used for online scenario or in actual driving condition thus dynamic programming has limited usage. Parallel hybrid electric vehicles are gaining popularity with each passing year.

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Today parallel hybrid electric vehicle is perhaps one of the most potential solution of global problems like fuel price increase, global warming, air pollution, climate change...etc because parallel hybrid electric vehicles deceases fuel consumption and carbon emissions when compared to gasoline vehicles. The main drawback of pure electric vehicles is that the battery technology has failed to advance much and therefore has limited the usage of pure electric vehicles per charge.

This paper presents a hybrid technique which combines fuzzy logic, rule based and ECMS algorithm for energy management in parallel hybrid electric vehicles. This hybrid technique gives improved solution for fuel consumption and it can be employed for both offline and online scenario. This paper has four sections. Section 2 shows the details of the vehicle structure and the vehicle modelling of parallel hybrid electric vehicles with various parameters and values. Section 3 gives details about the hybrid algorithm. Section 4 showcases the results and section 5 highlights the distinct advantages of this hybrid algorithm in conclusion section.

Vehicle Structure and Modelling

In Figure 1, the electric motor and internal combustion engine are connected in parallel with the transmission system. Figure 2 and figure 3 shows efficiency maps of ICE engine and electric motor. Figure 4 shows lithium ion battery circuit diagram and Table 1 shows values of various parameters used for structure and modelling the vehicle.

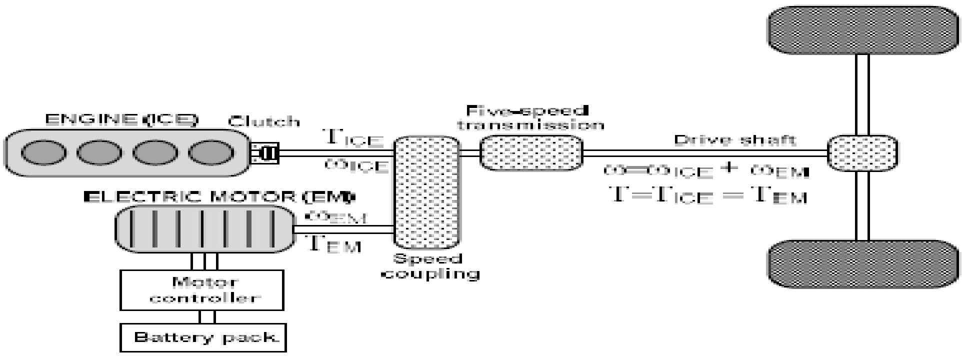

Figure 1: Parallel hybrid drive train

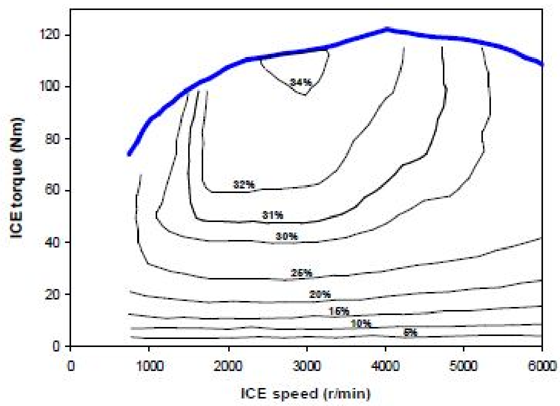

Figure 2: Torque-speed and efficiency map of the 65 kW ICE

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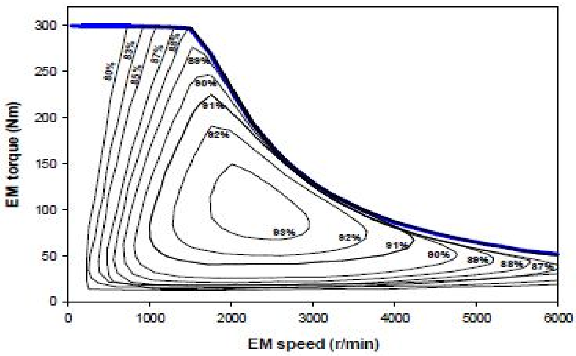

Figure 3: Torque-speed and efficiency map of the 50 kW EM (permanent magnet Synchronous motor)

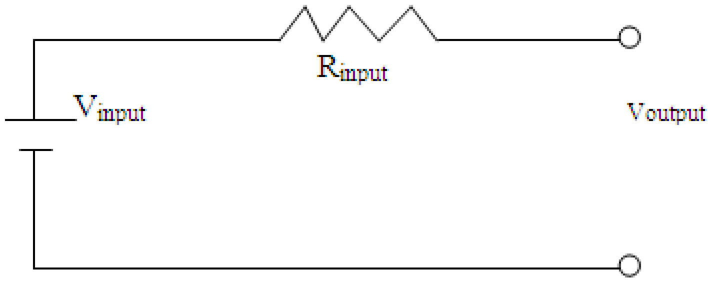

Figure 4: Simple Battery Model

Table 1: Values of various parameters used in modelling and structuring of the vehicle

1	$S_{frontal}$	**2.16 m^2**
2	a_{wheel}	0.29 m
3	W	1500 Kg
4	Trans1	0.9
5	Gear	15.5, 10.1, 6.8, 5.0, 3.8
6	drag	0.26
7	air	1.2 kg/m^3
8	angle	0^0
9	friction	0.01
10	bat	0.9 p.u.
11	gen	0.9 p.u.
12	icepower	65 KW
13	minsoc	0.2 p.u
14	maxsoc	0.9 p.u
15	minpower	-90 KW
16	maxpower	90 KW
17	minbat	-4 KW
18	maxbat	4 KW
19	nombat	4 KWh
20	zerobat	3.6 KWh
21	V_{input}	300 V

22	R_{input}	0.37 Ω

Electric motor and internal combustion engine are the two power sources used in parallel hybrids. Same gear boxes are used, so the angular speed of both engine and motor is supposed to be as shown in equation 1.

$$K_{ice}=K_{em} \quad (1)$$

Equation 2 calculates torque request

$$K_{request}=K_{em}+K_{ice} \quad (2)$$

The total force at the wheel is shown in equation 3.

$$X_{wheel}=W*a_{ec}+friction*W*gravity*\cos(angle)+ W*gravity*\sin(angle)+0.5*air*drag*S_{frontal}*vel^2 \quad (3)$$

Equation 4 calculates the tractive torque at the wheels

$$Tor_{wheel} = X_{wheel} *a_{wheel} \quad (4)$$

a_{wheel} is the radius of the tyre.

The request torque and power are calculated by equation 5 and 6

$$Tor_{requested} = Tor_{wheel}/Trans1*Gear \quad (5)$$

$$Pow_{requested}=Tor_{requested}*(vel/a_{wheel})*Gear \quad (6)$$

A simple battery model is shown in Figure 4. The energy of the battery at any time instant t is calculated by equation 7 and 8,

$$newbat=zerobat \pm \int Powerbattery(t)dt \quad (7)$$

$$Powerbattery=\frac{V_{output}^2 - V_{output}\sqrt{V_{output}^2 - 4P_{inv,DC}R_{input}}}{2R_{input}} \quad (8)$$

The state of charge (SOC) of the battery is calculated in equation 9

$$SOC=newbat/nombat \quad (9)$$

Various constrains considered are shown from equation 10 to 14. [8, 9]

$$P_{ICE(t)}\in[0,90] \quad (10)$$

$$P_{EM(t)}\in[-90,90] \quad (11)$$

$$P_{batt(t)}\in[-4,4] \quad (12)$$

$$Pow_{requested}=Pow_{EM}+Pow_{ICE} \quad (13)$$

$$SOC(t)\in[0.2,0.9] \quad (14)$$

The energy produced during regenerative mode is delivered to the battery pack, which is calculated in equation 15,

$$Energy_{regen}=1/2*bat*gen*W*(V_1^2 - V_2^2) \quad (15)$$

V_1 and V_2 are the velocities between which braking has been applied. Figure 2 and Figure 3 respectively displays efficiency maps of internal combustion engine [21] and electric motor.

Hybrid Algorithm (Fuzzy + Rule Based + ECMS)

The five mode of operation are: MODE 1 (only motor mode), MODE 2 (only engine mode), MODE 3 (engine + motor mode), MODE 4 (charging mode), and MODE 5 (regenerative braking mode). The hybrid algorithm has 2 parts in first part the mode 1, 2, 3 are selected by fuzzy logic and mode 4 and mode 5 are selected by IF THEN ELSE RULES. The reason of using fuzzy logic for mode 1, 2, 3 selections since mode 1, 2, 3 range or boundary is vague and not clear, there is lot of uncertainties in the lower and upper limit of speed or velocity for modes 1, 2, 3. During Mode 2 operation ICE drives the entire vehicle but from the efficiency map of ICE it is not clear what is exact speed range of ICE in which it gives best efficiency, it can be 25 to 55 km/hr or 30 to 60 km/hr or 22 to 57 km/hr, therefore seen the uncertainties, selection of mode 1, 2, 3 is done by fuzzy controller, fuzzy works best when there is uncertainties in the system. Generally mode 1 is most suitable at low speed, while mode 2 is suitable at medium speed and mode 3 is suitable at high speed but exact value of speed where this change in mode take place is difficult to say. The modes 4 and 5 are selected by IF THEN ELSE rules since exact boundary can be marked for modes 4 and mode 5 operations. Suppose if acceleration of vehicles is less than zero than mode 5 is selected and suppose when charge of the battery is less than 0.55 than mode 4 is selected, so exact prediction can be done and there is no uncertainties in the system so IF THEN ELSE RULES are used to select mode 4 and mode 5. IF THEN ELSE RULES are defined below

IF *acceleration* < 0
Mode 5 (regenerative braking) is selected
ELSE
MODE 1, 2, 3 are selected by **fuzzy controller**
IF *SOC* < 0.55
Mode 4 (battery charging) is selected

Figure 5, 6, 7, 8 and 9 describes various components of fuzzy controller used for selecting mode 1, 2 and 3. The input to fuzzy controller is velocity and output is the mode selection, 1 input and 1 output.

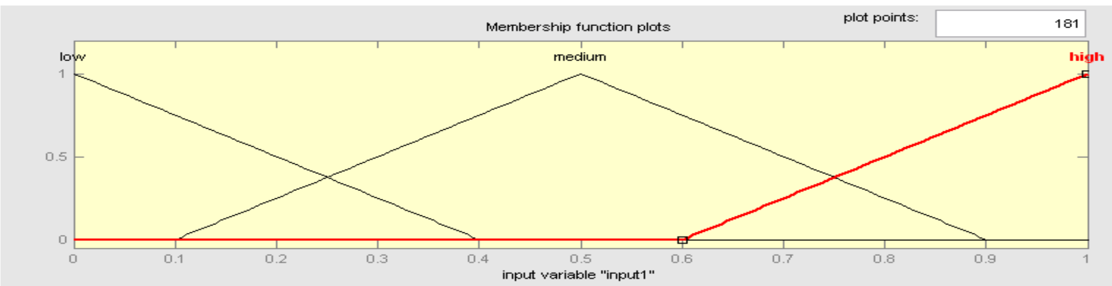

Figure 5: Fuzzy Input membership function

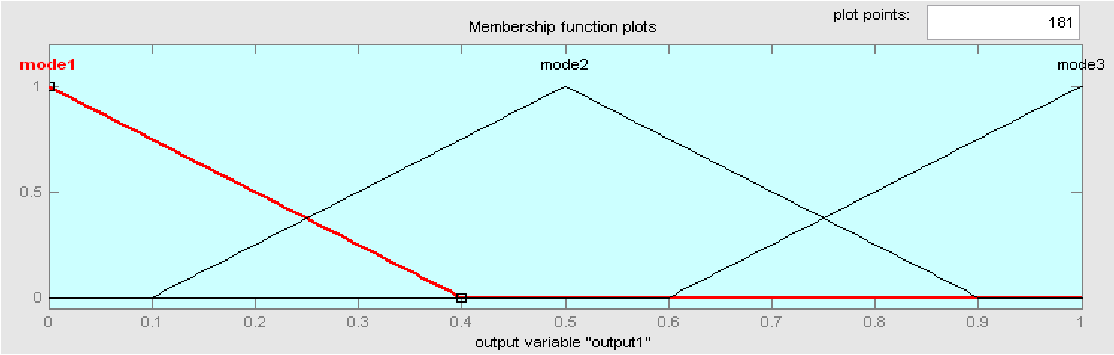

Figure 6: Fuzzy Output membership function

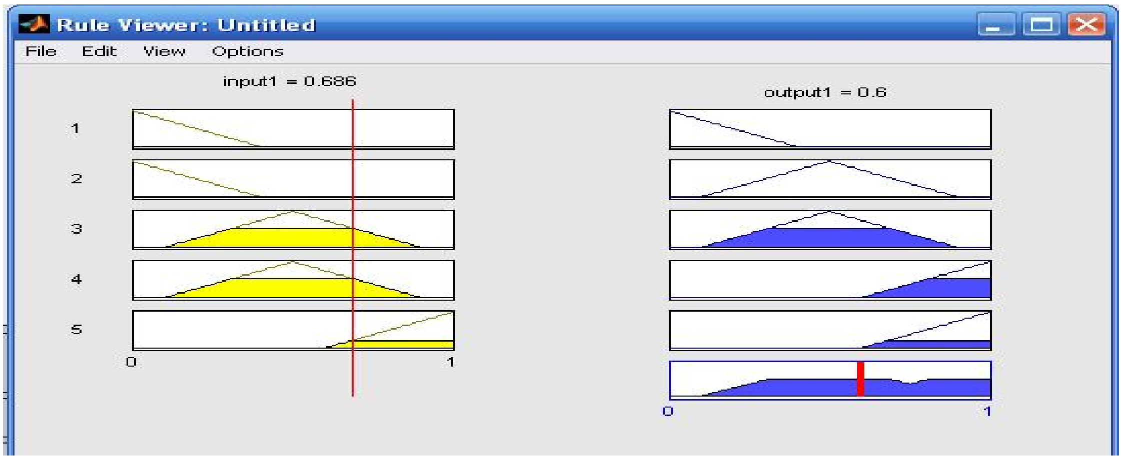

Figure 7: Fuzzy Rules represented in diagram form

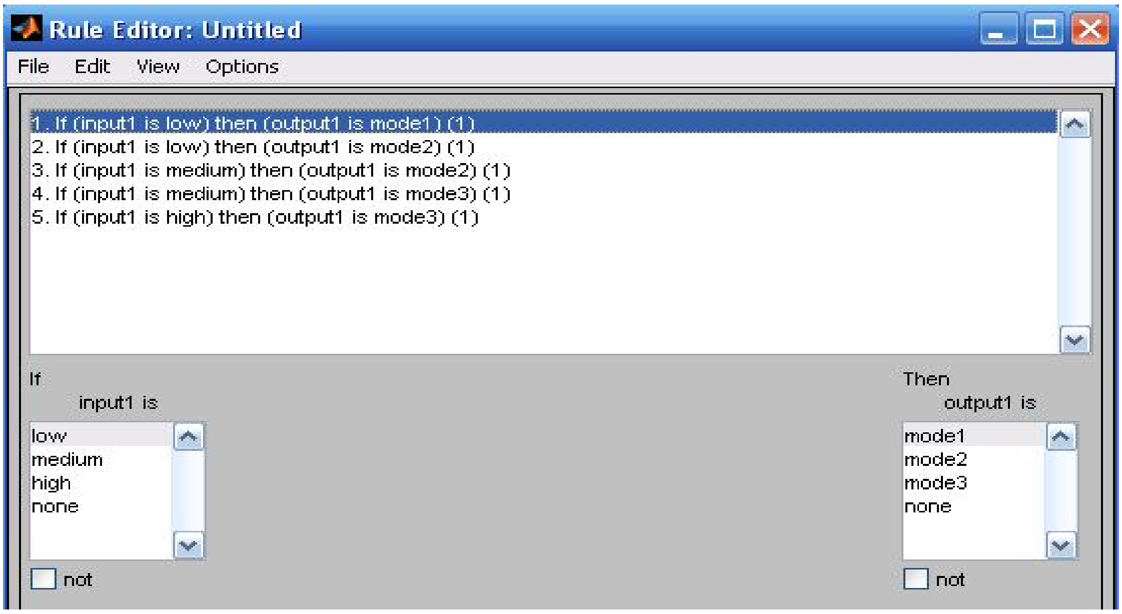

Figure 8: Simple Fuzzy Rules

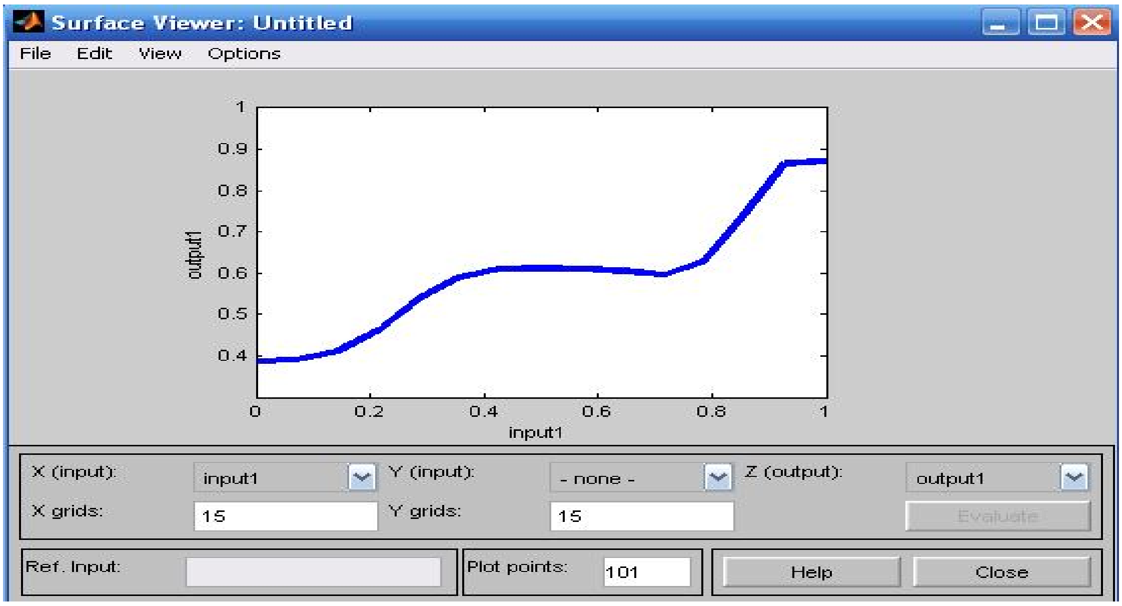

Figure 9: Variation of Fuzzy Output and Input

After prediction of mode is done, the power requested and SOC is calculated for each mode of operation. The power requested in mode 3 is further optimized by ECMS algorithm since the power requested obtained is not optimal. ECMS algorithm finds best combination of power sharing between engine and motor during operation of mode 3. ECMS algorithm is explained in detail below. The ECMS algorithm is an on-line optimization method which attempts minimizing the fuel consumption at every time instance. ECMS is focused to determine the best power sharing between the ICE and the battery to cope with the power demand. ECMS defines an instantaneous cost function based on the equivalent fuel consumption. This is calculated as the fuel mass flow rate (it is a function of the power delivered by the (ICE) plus the equivalent fuel flow rate due to the EM. This latter is a function of the equivalence factor (the factor applied to transform the electric power consumption into the equivalent fuel consumption) and the EM output power among others [9].The main objective of the ECMS algorithm is to optimize the overall fuel consumption by minimizing the fuel consumed by the ICE [9]. The objective function to be minimized by the ECMS algorithm is given as,

$$J(t)= \int_0^t meq(t)dt = \int_0^t [mice(t) + mbattery(t)]dt \quad (16)$$

where $meq(t)$ is the fuel consumption of the ICE in kWh and $mbattery(t)$is the equivalent fuel consumed by the vehicle during battery discharging.

For mode 3, i.e. when the battery is discharging, the equivalent fuel consumed by the battery is,

$$mbattery(t)= K \cdot P / Q \cdot \eta \quad (17)$$

Where K is the equivalence factor, which acts as a weighting factor for the electric energy. This factor affects the optimum power sharing between the engine and the motor. Q is the gasoline lower heating value and η is the drive train efficiency.

The SOC of the battery is not explicitly considered in the objective function, as described in (16). The SOC must be maintained within a predetermined range to ensure satisfactory vehicle behaviour and adequate battery useful life. To take into account the current SOC value, a feedback adjustment is often applied to the weighting factor *K* in (17) and (18) as follows,

$$K = EQF \cdot Kp \cdot Ki \quad (18)$$

For a parallel hybrid configuration, the suggested value of *EQF* is 2.4 whereas *Kp* and *Ki* are the gains, whose values are calculated as follows,

$$X(t) = \frac{SOC(t) - SOC_{ref}/2}{\Delta SOC/2} \quad (19)$$

Where SOC_{ref} is set to 27% and ΔSOC is set to 4%. In addition

$$K_p = 1 - x_1^3 \quad (20)$$

$$X_2(t) = 0.01(SOC_{ref} - SOC(t)) + 0.99\, X_2(t - \Delta t) \quad (21)$$

$$K_I = 1 + \tanh(12x_2) \quad (22)$$

Δt is the time step taken during simulations.

Table 2: Summary of the Proposed Hybrid Algorithm

Mode	Optimization Method
Mode 1 (Electric motor only)	FUZZY LOGIC
Mode 2 (ICE only)	FUZZY LOGIC
Mode 3 (Engine + motor)	FUZZY LOGIC + ECMS
Mode 4 (Battery charging)	IF THEN ELSE
Mode 5 (Regenerative braking)	IF THEN ELSE

Results

Japanese 15 mode driving cycle has been employed to test the hybrid technique. Simulation results are displayed in figures 8, 9, 10, 11. The hybrid algorithm (Fuzzy logic + Rule Based + ECMS) fuel consumption result is compared with result of only ECMS optimization technique. The hybrid algorithm shows **5.05%** decrement in fuel consumption as compared to fuel consumption obtained by ECMS only optimization technique. The comparison results are shown in Table 3.

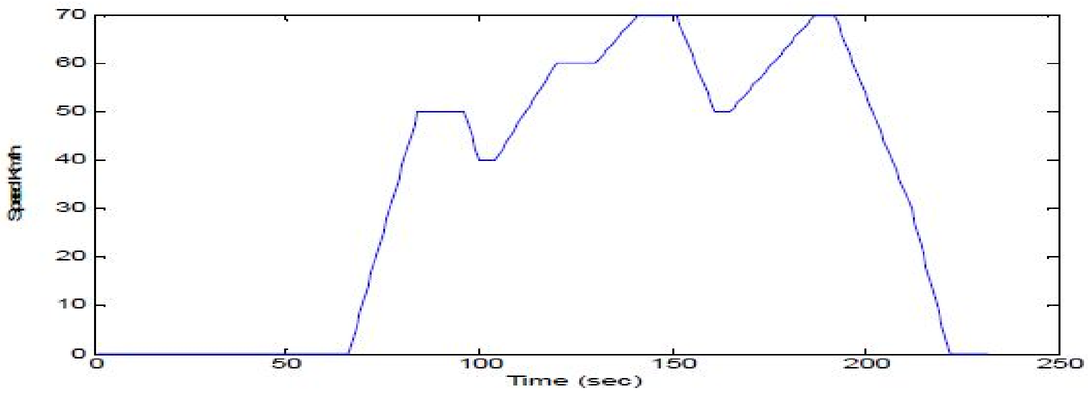

Figure 8: Japanese 15 mode driving cycle

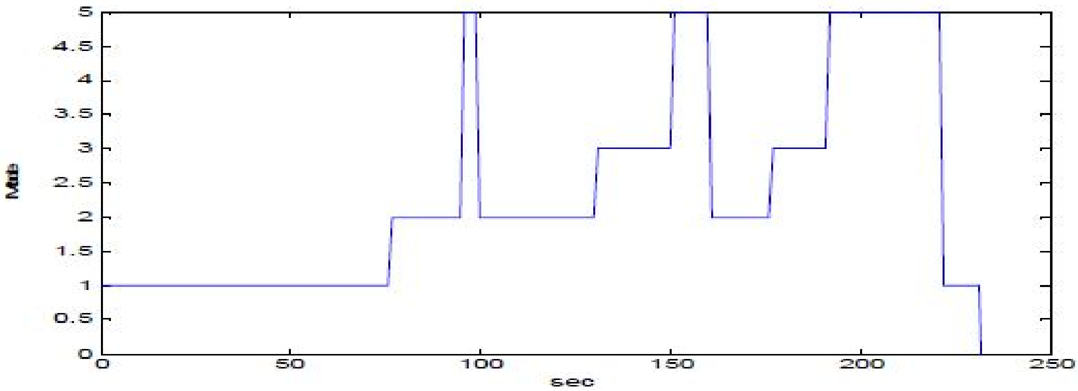

Figure 9: Modes predicted by Fuzzy and Rule Based

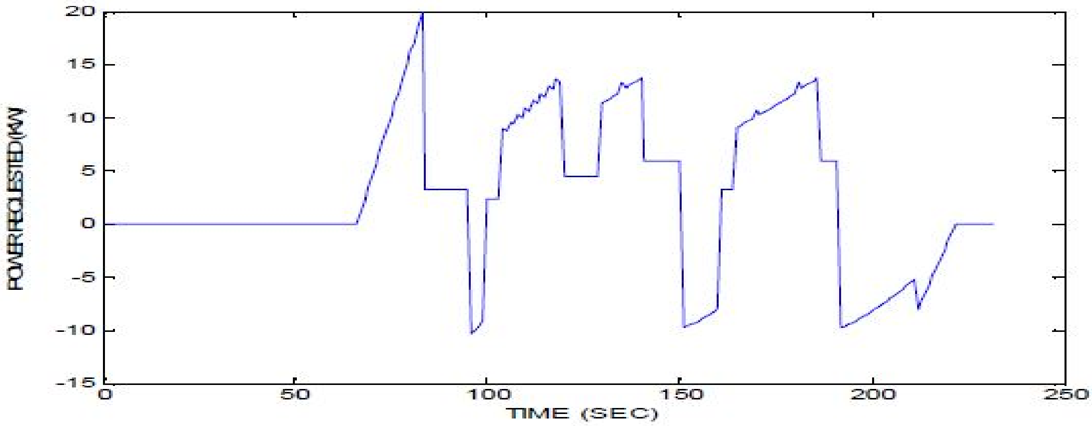

Figure 10: Power requested plot of Japanese 15 mode driving cycle

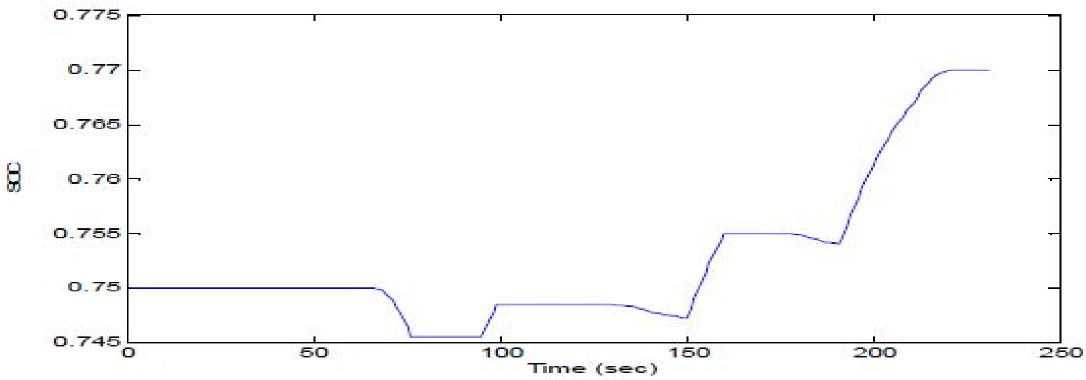

Figure 11: SOC variations of lithium Batteries for Japanese 15 mode driving cycle

Table 3: Comparative Results of ECMS only and Fuzzy + Rule based + ECMS hybrid technique

Algorithm	Fuel consumption (L/100 km)*(Japanese 15 mode driving cycle)
ECMS only	3.90
Fuzzy Logic+ Rule Based + ECMS	**3.705**

**It has been assumed that the LHV of gasoline is 9.2 kWh/L*

Conclusion

This paper presents a hybrid algorithm which combines three optimization techniques that is rule based fuzzy logic and ECMS. The main advantages of this hybrid algorithm that this algorithm can be used for both online and offline scenario and it gives **5.05%** improvement in fuel consumption for Japanese mode 15 drive cycle when compared with only ECMS algorithm.

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